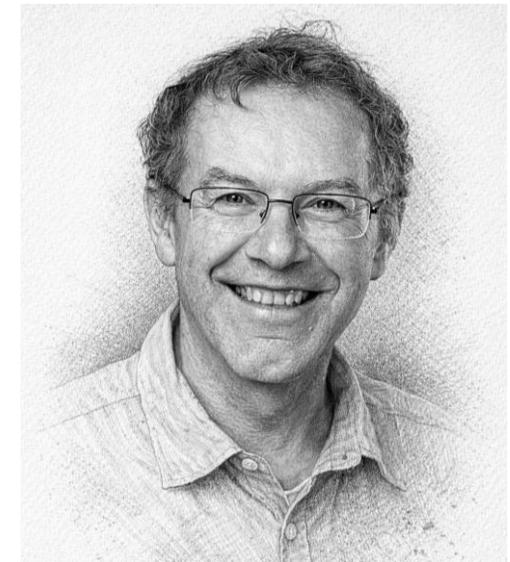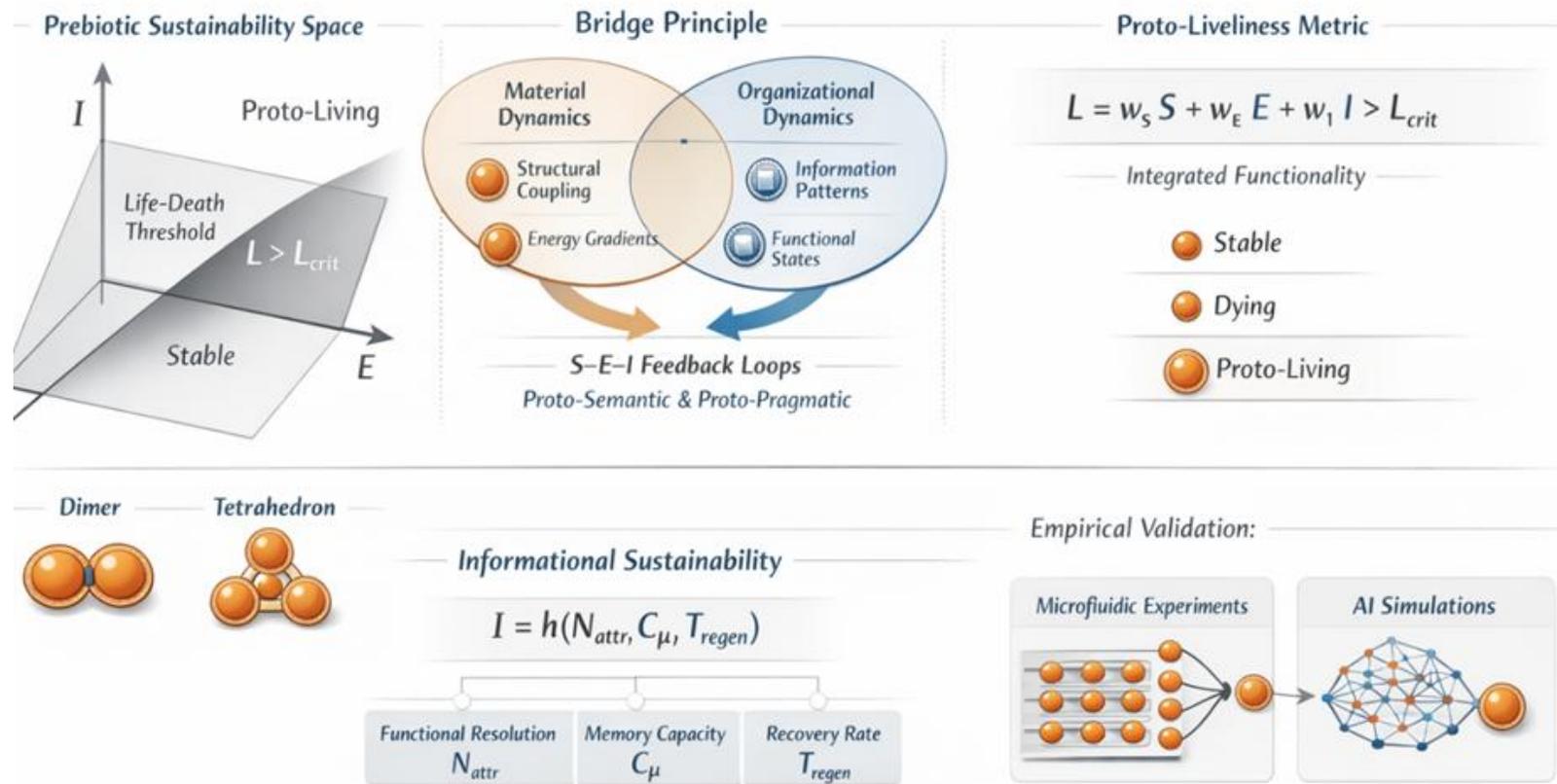# From **Prebiotic Sustainability** to **Proto-Liveliness**:
A **Biocomputational Framework** with Structural, Energetic and Informational Metrics for Protocell Cluster Evolution

Michael Massoth

Hochschule Darmstadt (h_da)

BIOTECHNO-2026 | Valencia

Three-Dimensions Sustainability Framework (S-E-I)

Structural sustainability (S)

- membrane integrity
- cluster connectivity
- stable distances & contact graphs

Metrics: lifetime, breakup rate, $\langle k \rangle$, $\langle L\_nn \rangle$

Energetic sustainability (E)

- persistence of ion/proton gradients
- $\tau\_gradient \geq \tau\_diff$ as criterion
- ΔpH pockets as usable energy

Metrics: ΔpH, $\tau\_gradient$, heat proxy

Informational sustainability (I)

- recurrence of macrostates
- attractor return dynamics
- ε-machine stability of transitions

Metrics: P_return, T_return

Mapping of Prebiotic Sustainability Levels to Reliability Engineering Concepts

Prebiotic Sustainability Level	Reliability Engineering Analogon	Representative Measurement / Metric
Stability	Low hazard rate / high Mean Time To Failure (MTTF)	Cluster break-up rate; mean lifetime of dimer or cluster structures
Persistence	State retention time / operational availability	Ratio $\tau_{gradient}$ / τ_{diff}; duration of stable ion or proton gradients
Regenerability	Mean Time To Recovery (MTTR) / recoverability	Reassembly time after perturbation; return probability to functional attractor state

Structural Distance D(t,Δt) from Order-Parameter Vector θ(t)

θ(t)

- ▦ $\langle L_{nn} \rangle$
- Σ $\sigma(L_{nn})$
- $N_{cluster}$
- $\langle k \rangle$
- $f_{cluster}$
- $\langle \Delta pH_{gap} \rangle$
- Σ $\sigma(\Delta pH_{gap})$
- $\tau_{gradient}$
- T_{return}

$D(t, \Delta t)$ δ

$D < \delta$
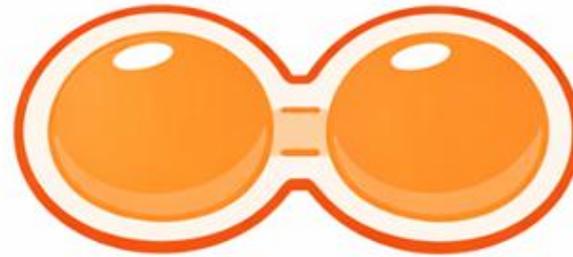
$$D(\text{Struktur}, t + \Delta t \mid t) = \left(\sum_{i=1}^{n} w_i \left[\frac{\theta_i(t + \Delta t) - \theta_i(t)}{\theta_{i,\text{ref}}} \right]^2 \right)^{1/2}$$

Core Idea

$$L = w_S \cdot S + w_E \cdot E + w_I \cdot I$$

$$L > L_{crit}$$
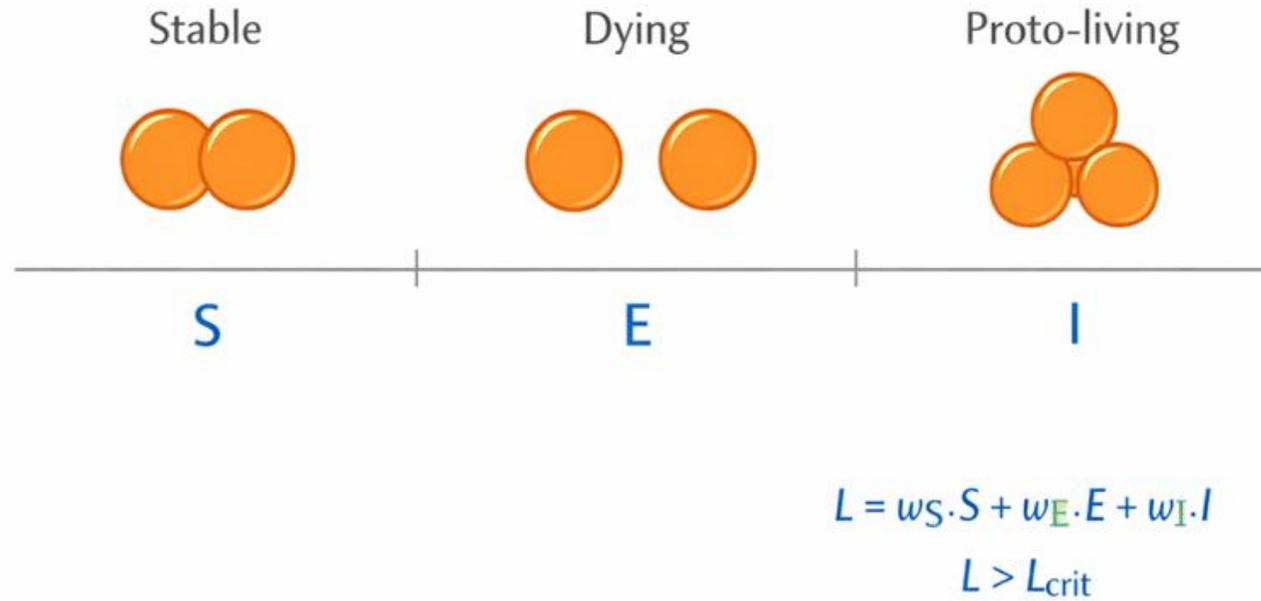
Consistent physical–functional framework

Level	Formal Expression	Interpretation
Statistical	$p(x)$; $\langle x^n \rangle$; $S(\omega)$	Ensemble distributions, moments, spectra, and fluctuation statistics
Syntactic	$x(t + \Delta t) = F(x(t))$	Material transition laws governing physical dynamics
Semantic	$P(\, x(t + \Delta t) \in A \mid$ disturbance $) \to 1$	Persistence-relevant attractor A defines functional meaning
Pragmatic	$x(t + \Delta t) = F(x(t), y(t))$ $y(t + \Delta t) = G(y(t), x(t))$	Organizational feedback via $y(t)$ modulating future dynamics

Transition from statistical description to pragmatic, function-modulating dynamics through recurrent stabilization and organizational feedback. Semantic meaning arises from persistence-oriented attractors, while pragmatic function emerges when organizational variables causally modulate future system dynamics.
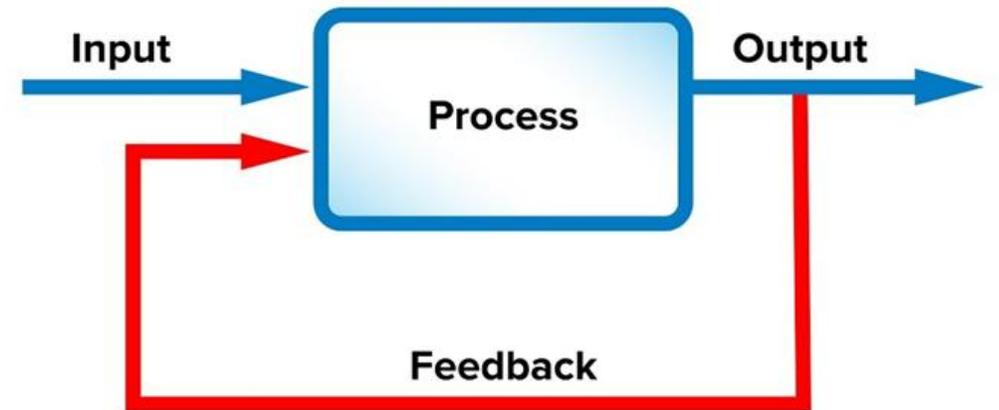
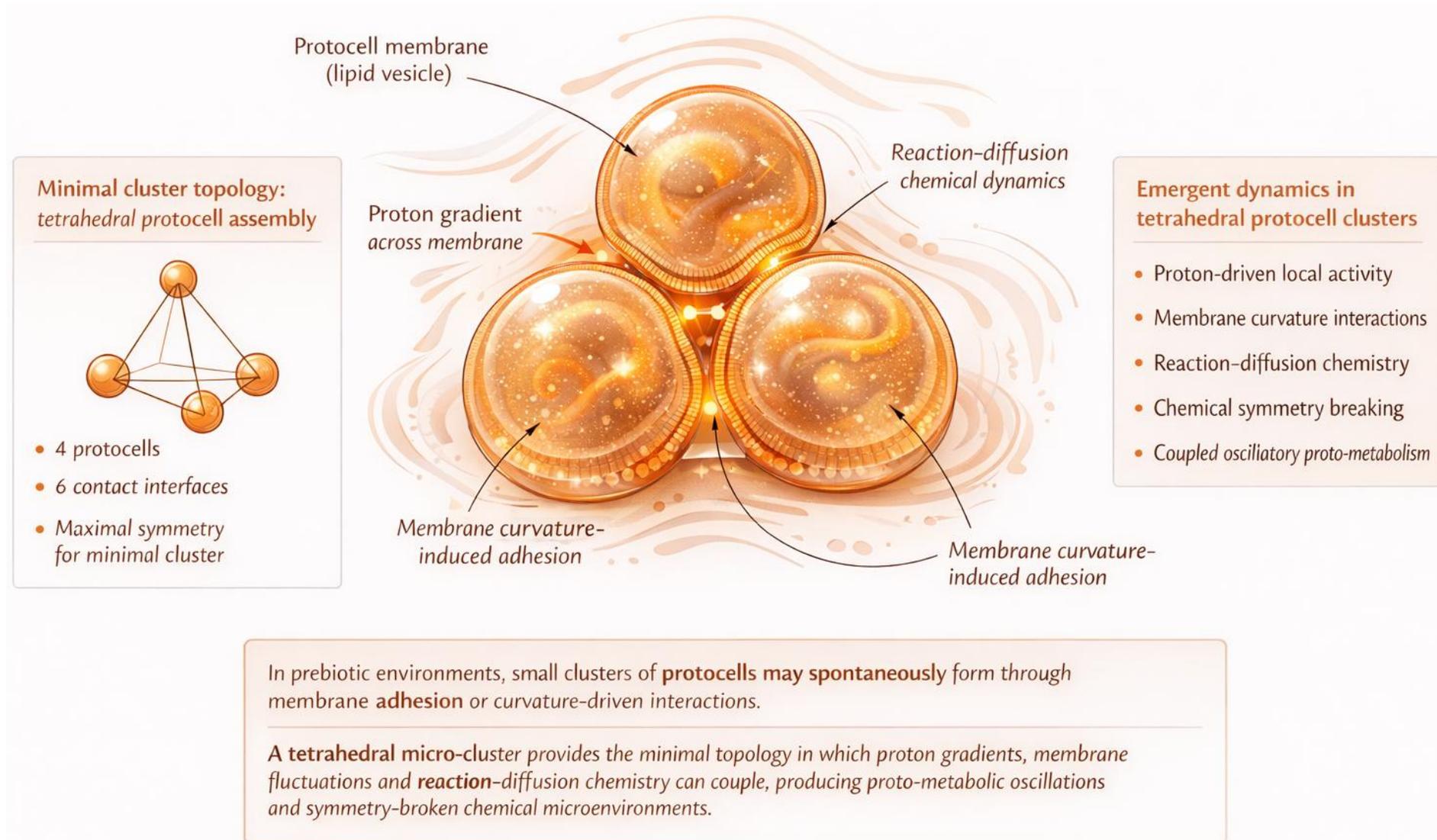# Coupled structural, energetic, and informational feedback loops
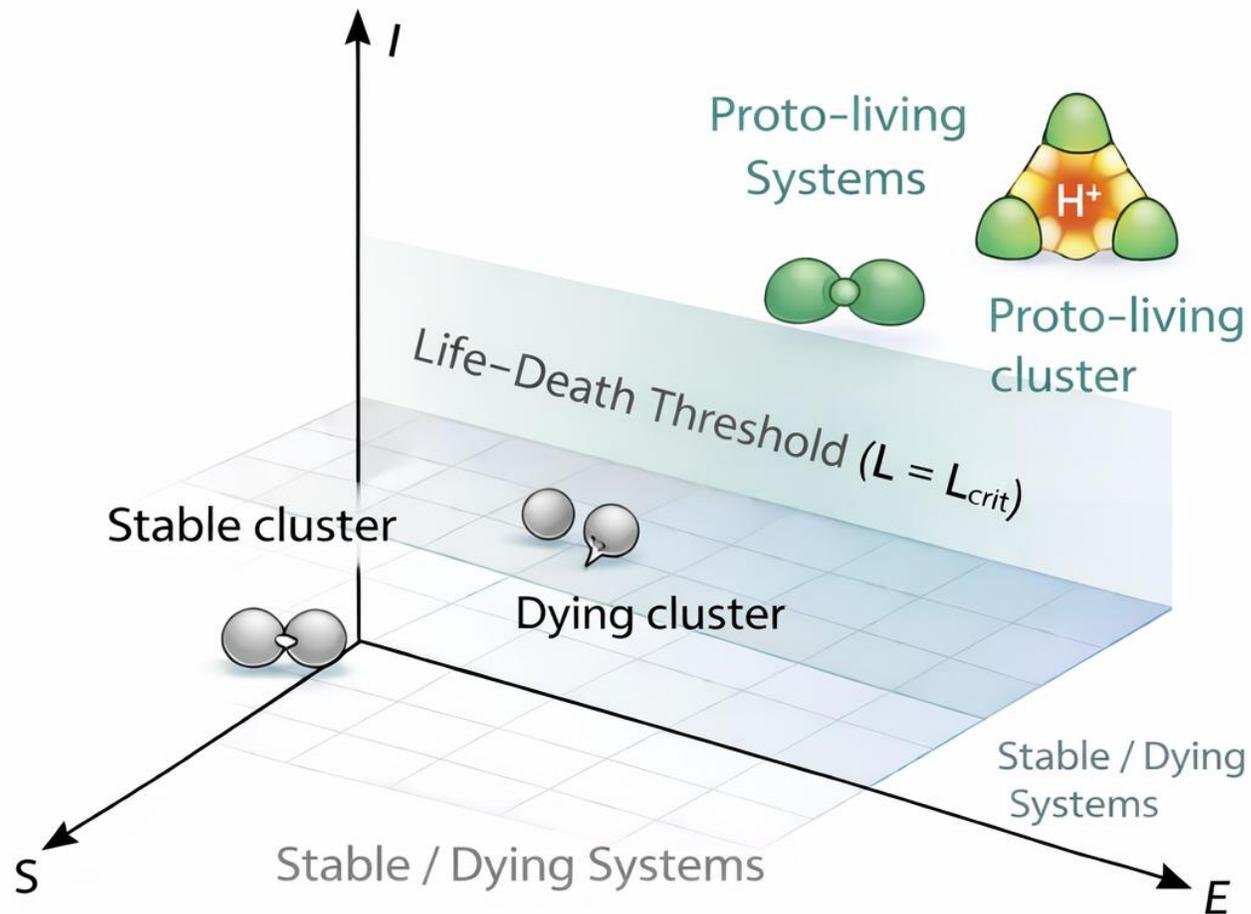

Structural loop (S)

Energetic loop (E)

Proto-liveliness

Informational loop (I)

Input → Process → Output

Feedback
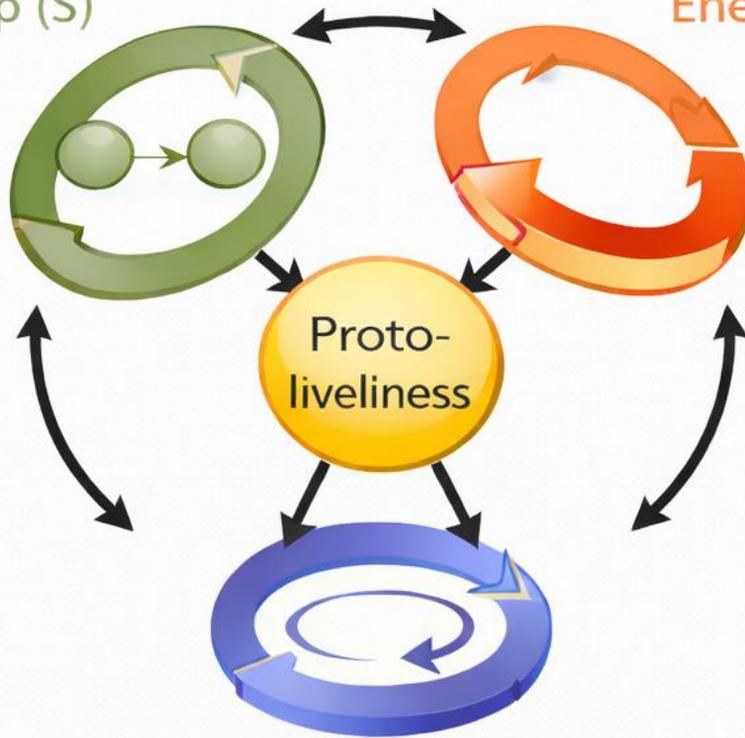
Looking for Local Activity Zones / Principle

Minimal cluster topology: tetrahedral protocell assembly

- 4 protocells
- 6 contact interfaces
- Maximal symmetry for minimal cluster

Protocell membrane (lipid vesicle)

Proton gradient across membrane

Reaction–diffusion chemical dynamics

Membrane curvature-induced adhesion

Membrane curvature-induced adhesion

Emergent dynamics in tetrahedral protocell clusters

- Proton-driven local activity
- Membrane curvature interactions
- Reaction–diffusion chemistry
- Chemical symmetry breaking
- Coupled oscillatory proto-metabolism

In prebiotic environments, small clusters of **protocells may spontaneously** form through membrane **adhesion** or curvature-driven interactions.

A **tetrahedral micro-cluster** provides the minimal topology in which proton gradients, membrane fluctuations and **reaction**-diffusion chemistry can couple, producing proto-metabolic oscillations and symmetry-broken chemical microenvironments.
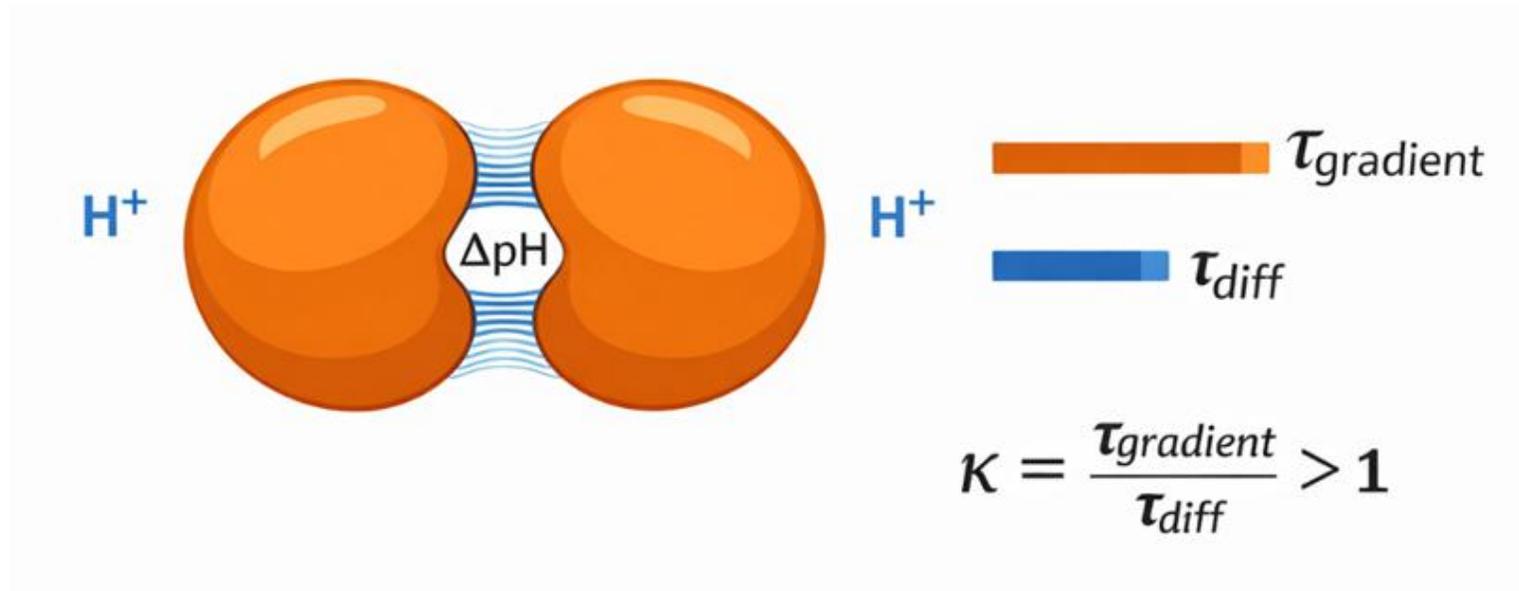
Prebiotic sustainability space and life–death threshold

Move from passive stability to measurable proto-liveliness:

- Proto-liveliness requires coupled S–E–I sustainability

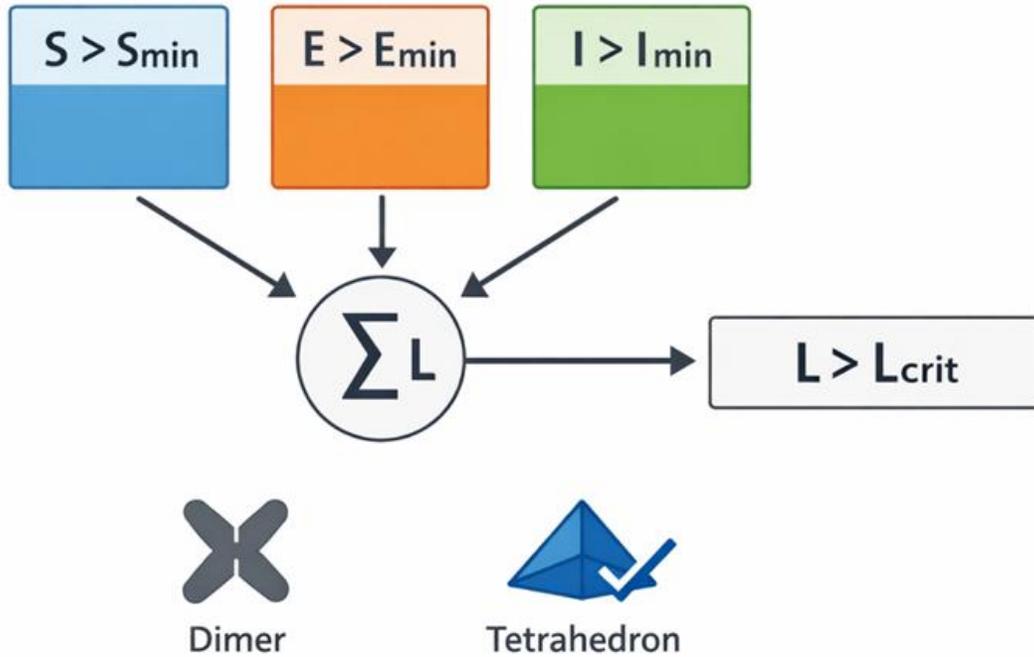- Goal: define quantitative Life–Death threshold

Energetic Sustainability E (κ > 1)

$$\kappa = \frac{\tau_{gradient}}{\tau_{diff}} > 1$$

Gradients must outlive diffusion (κ)

- Gradient energy: $\Delta\mu H^+ \sim k_B T \cdot \Delta pH$

- Efficiency η: power allocated to stabilization
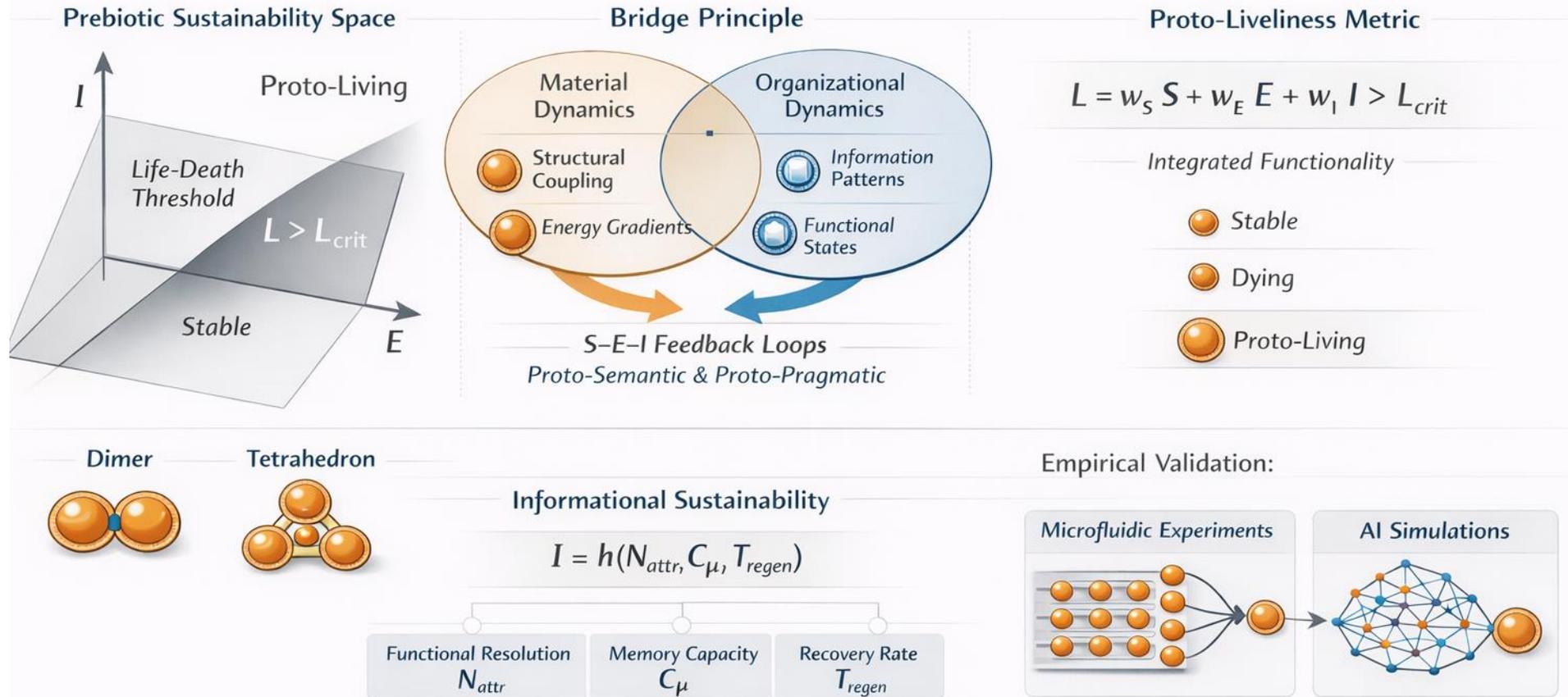
- High E → persistent non-equilibrium organization

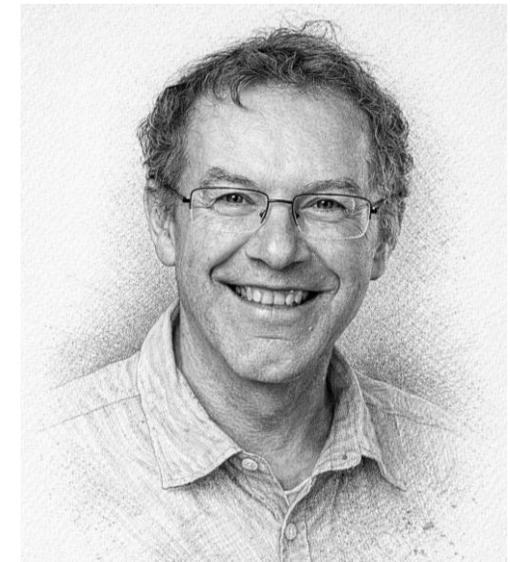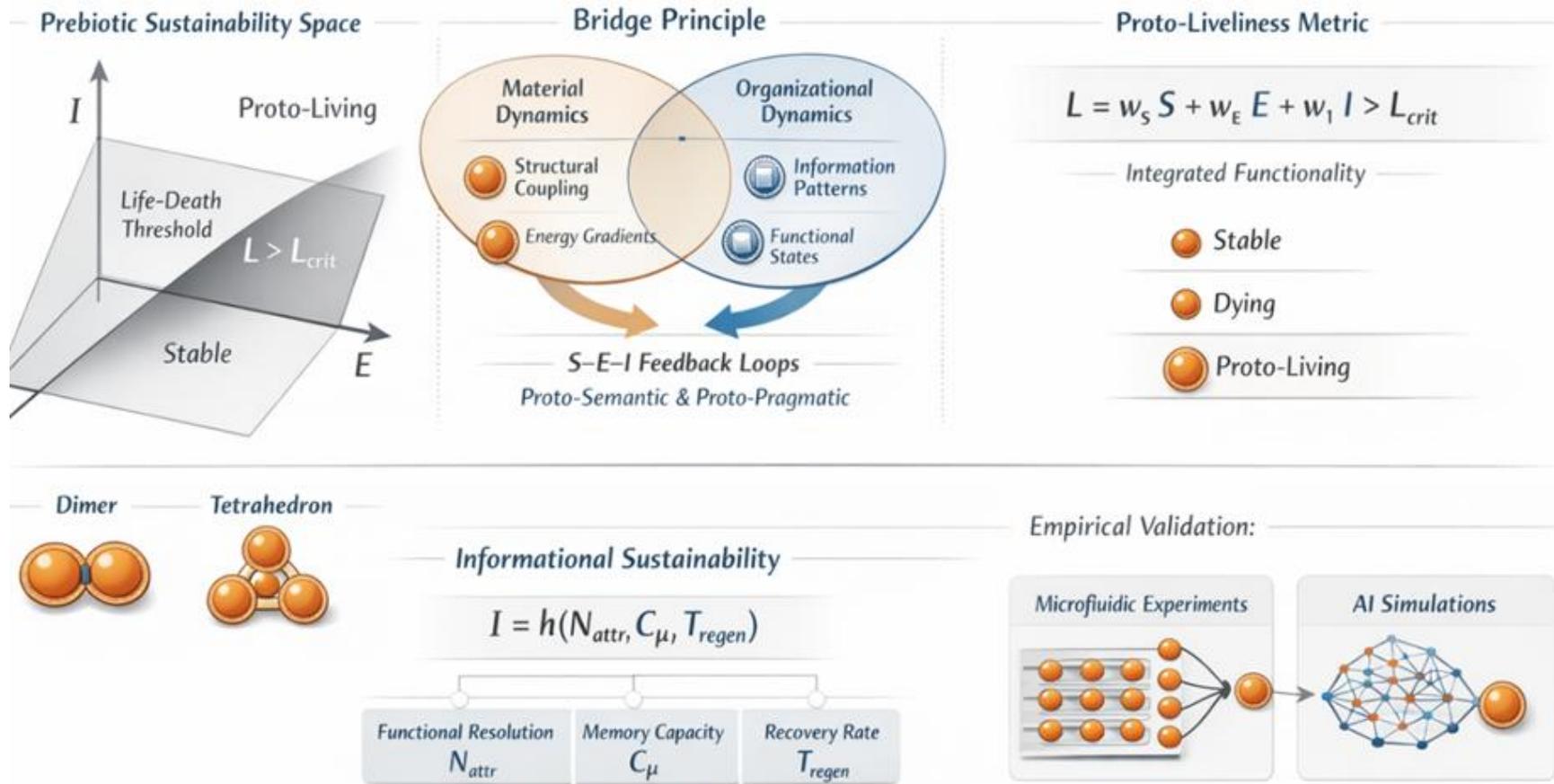# Life–Death Threshold Logic (**Three Gates**)

Take-home Message

From Prebiotic Sustainability to Proto-Liveliness:
A Biocomputational Framework with Structural, Energetic and Informational Metrics for Protocell Cluster Evolution

Thank you very much for your attention.
Are there any questions?

Michael Massoth
Contact:
michael.massoth@h-da.de